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Electrical resistivity in spin glass CuMn

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The electrical resistivity is discussed, providing a direct measurement of the critical exponent β for a spin glass CuMn. CuMn alloys with magnetic impurity concentrations ~ 0.7 –4.5 at. % exhibit the characteristic spin glass cusp in low field ac susceptibility at temperature T_f . The magnetic contribution to the resistance of this alloy increases with temperature below T_f and is constant above T_f . By using the exchange interaction between the conduction electrons and the unpaired electrons localized on the Mn ion as a perturbation and by applying the Boltzmann transport equation, the electrical resistivity is shown to be related to the order parameter q . Below the freezing temperature, scattering can be caused by deviation of the spin from its ground state. As the temperature rises, the resistivity will increase, too. Above the freezing temperature, each spin behaves perfectly independently and gives rise to a constant resistivity. So the critical exponent β of spin glass order parameter q can therefore be determined by fitting the theory to measured data. It also can be shown that specific heat is related to the temperature derivative of $\rho_{\text{mag}}(T)$ for ordered magnetic moment material.

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I. INTRODUCTION

Ford and Mydosh [1] measured the electrical resistivity of noble-metal-host 3d solute spin glass alloys such as gold and copper containing traces of the transition element represented by manganese and chromium, and found the decrease of the resistivity at low temperature. Campbell [2] considered the electrical resistivity of spin glass in terms of the elementary excitations of Walker and Walstedt [3]. Campbell's approach had good agreement with experimental data. Meanwhile, the s-d model of transport in transition metals and alloys was proposed by Fateev and Wiegmann [4] in 1981. The effect of s-d interaction between conduction electrons and d shell of magnetic ion was devised by Mott [5]. Here, a simple derivation of resistivity due to s-d exchange interaction is given. It can be shown that the spin glass phase of dilute magnetic impurity in noble metal is related directly to the magnetic impurity resistivity. The experimental data from Ford and Mydosh [1] is discussed.

II. EXPERIMENTAL RESULTS

Resistivity as a function of temperature for CuMn alloys is plotted in the insert of Figs. 1 and 2. CuMn alloys with magnetic impurity concentration ~ 0.7 – 4.5 at. % exhibit the characteristic spin glass cusp in low field ac susceptibility at freezing temperature, T_f . The shift of T_f can be neglected for various frequencies [6].

In order to eliminate the temperature dependent contribution to the resistivity due to electron-phonon scattering, we subtract the temperature-dependent phonon-resistivity for the host metal [7]. The remaining quantity is a measure of the specific magnetic scattering contribution to the resistivity. Figures 1 and 2 show ρ_{mag} at low temperature for two

samples. The insert of each figure indicates the ρ_{measured} and ρ_{phonon} . We see clearly that ρ_{mag} increases with temperatures and then saturates above T_f .

III. THEORY

To calculate the contribution to the electrical resistivity due to spin fluctuation, the following standard assumptions are made: (i) Matthiessen's rule is valid. (ii) The s-d exchange interaction is weak enough to treat by the lowest-order Born approximation. (iii) The energy shift of spin fluctuations is very small compared with the energy of the electron, so that the scattering of the electron is elastic. (iv) The resulting scattering is adequately described by a simple variational estimate based on the Boltzmann equation. For the simplified problem, it is sufficient to describe the current carriers by a spherical Fermi surface.

The electrical resistivity due to spin fluctuations is due to conduction electrons of Cu (labeled by k, σ) being scattered by spins of Mn which are taken to be localized at position \vec{R}_n . The weak coupling between the conduction electrons and the localized spins is of short range s-d exchange origin [8]. The Hamiltonian of the entire system may be written as

$$H = H_0 + H' \quad (1)$$

$$\text{and } H_0 = \sum_{k, \sigma} \epsilon_{k\sigma} a_{k\sigma}^\dagger a_{k\sigma} + \sum_{i < j} J_{ij} \vec{S}_i \cdot \vec{S}_j \quad (2)$$

$$H' = \sum_n \sum_{k, k'} \sum_{\sigma, \sigma'} \langle k | A_{sd}(\vec{r} - \vec{r}_n) | k' \rangle \langle \sigma | s | \sigma' \rangle a_{k\sigma}^\dagger a_{k'\sigma'} \vec{S}_n \quad (3)$$

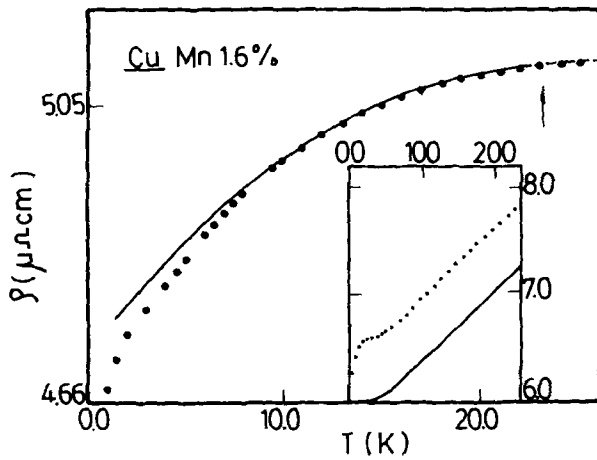


Fig.1 Resistivity data (closed circle) from magnetic contribution as a function of temperature for 1.6 at. % sample of CuMn. The arrow indicates the position of T_f from the ac susceptibility measurements.

where H' is s-d exchange interaction between localized spins and conduction electrons. $|k\rangle$, $|s\rangle$ denote wave number and spin-projector-state of conduction electron. The transition probability due to s-d interaction has the form

$$S(\underline{k}, \underline{k}') = \frac{2\pi}{\hbar} |\langle \underline{k}', s' | H' | \underline{k}, s \rangle|^2 \delta(E(\underline{k}', s') - E(\underline{k}, s)) \quad (4)$$

The state $|\underline{k}, s\rangle$ represents the \underline{k} state of conduction electrons and s state of localized spins. After calculating the matrix elements of the spin operator $\langle s | \hat{S}_i | s' \rangle$, we rewrite $S(\underline{k}, \underline{k}')$ as

$$\frac{2\pi}{\hbar} |\langle \underline{k}', s' | \sum_n A_{sd}(\underline{r} - \underline{r}_n) \hat{S}_n | \underline{k}, s \rangle|^2 \delta(E_{\underline{k}'} + E_s - E_{\underline{k}} - E_s) \quad (5)$$

We choose a trial function, $\phi_{\underline{k}} = \hat{v}_{\underline{k}}$, in the variational solution of the Boltzmann transport equation [10] and use the Fourier integral form to express the δ function in Eq. (5) and assume the coefficient $A_{sd}(\underline{r} - \underline{r}_n)$ is either non-zero, constant, A_{sd} , or zero. The s-d effect only takes place when the conduction electron reaches a certain distance from the magnetic impurity. The resistivity of this system becomes

$$\rho_{\text{mag.}} = \frac{16\pi^6}{kT} \left\{ \sum_{\underline{k}} \sum_{\underline{k}'} \sum_s \sum_{s'} A_{sd} A_{sd} \int_0^\infty dt \langle s | \sum_n \hat{S}_n | s' \rangle \langle s' | \sum_m \hat{S}_m(t) | s \rangle \exp(-i(\epsilon_{\underline{k}} - \epsilon_{\underline{k}'} + \hbar^{-1})t) f_0(\epsilon) (1 - f_0(\epsilon')) \right. \\ \left. (\hat{v}_{\underline{k}} - \hat{v}_{\underline{k}'})^2 \right\} / \left\{ e^2 \left(\sum_{\underline{k}} v_{\underline{k}}^2 \frac{\partial f}{\partial \epsilon} \right)^2 \right\} \quad (6)$$

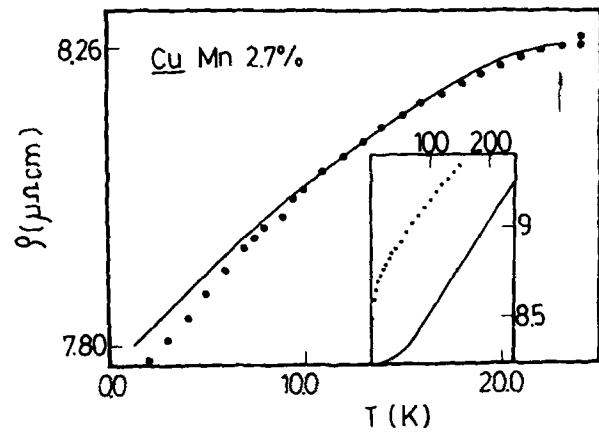


Fig.2 Resistivity data (closed circle) from magnetic contribution as a function of temperature for 2.7 at. % sample of CuMn. The arrow indicates the position of T_f from the ac susceptibility measurements.

To simplify the calculation, we do the integration of the time correlation function of spin and set it as

$$\langle \sum_n \hat{S}_n \cdot \sum_m \hat{S}_m(\infty) \rangle_T - \langle \sum_n \hat{S}_n \cdot \sum_m \hat{S}_m \rangle_T$$

where $\hat{S}_m(\infty)$ represents the easy axis of freezing spin.

In the approximation that the Fermi energy is much larger than the s-d exchange energy, we consider elastic collision of electron and sum \underline{k} , \underline{k}' over the spherical Fermi surface. Finally, we have the resistivity is proportional to magnetic impurities.

$$\rho_{\text{mag.}} \propto - \langle \sum_n \hat{S}_n \cdot \sum_m \hat{S}_m(\infty) \rangle_T + \langle \sum_n \hat{S}_n \cdot \sum_m \hat{S}_m \rangle_T \quad (7)$$

According to E-A [11], the spin glass phase is characterized by a nonvanishing value, q , of the different time correlation of a spin at a given site.

$$q \equiv \langle \hat{S}_i \cdot \hat{S}_i(\infty) \rangle_T = (1 - \frac{T}{T_f})^\beta \quad \text{for } T < T_f$$

$$q \equiv 0 \quad \text{for } T > T_f \quad (8)$$

Also, there is no spatial correlation of spin,

$$\langle \hat{S}_i \cdot \hat{S}_j \rangle_T = 0, \quad \text{for } i \neq j.$$

$$\rho_{\text{mag.}} = A_1 + A_2(1 - q) = A_1 + A_2 \{ 1 - (1 - \frac{T}{T_f})^\beta \} \quad (9)$$

We can see that in preferred direction there is no scattering due to this s-d exchange interaction. Above the T_f , each spin \hat{S}_n behaves perfectly independently and has no easy axis, the conduction electrons are scattered at each localized spin. So $\rho_{\text{mag.}}$ keeps constant above T_f . For the resistivity due to other impurities, the constant A_1 is added into Eq.

(9). The spatial correlation between spins, $\sum_{i,j} \langle \vec{S}_i \cdot \vec{S}_j \rangle_T$, is dominant in the ordered magnetic moment material. So the specific heat of those materials can be obtained by the temperature derivative of $\rho_{\text{mag.}}(T)$. This is consistent with the results of S. Alexander 12 et. al.

IV. CONCLUSIONS

The parameters A_1 , A_2 and β were determined by fitting equation (9) to the experimental data. The results have been collected in Table I. The fits are shown in Figs. 1 and 2. It can be noted that the value of β are compatible with sound velocity measurement [13] and theoretical prediction.

This model is based on the assumption that the current is carried mainly by electrons of Cu. Through s-d exchange interaction, the electrical resistivity varies with temperature. We have the evidence of spin-glass phase transition and determine the critical exponent of E-A order parameter.

Table I. Parameters obtained from fitting the electrical resistivity

CuMn	A_1	A_2	β
0.7 at %	2.13	0.20	2.17
1.6 at %	4.70	0.36	1.85
2.7 at %	7.76	0.50	1.45
4.4 at %	11.94	0.68	1.38

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